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Application of Cross-correlation Analysis Method for Measurement of the Fluid Flow Rate Based on X-ray Radiation

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In this work, we have demonstrated a principal scheme of application of cross-correlation analysis method for the determination of the velocity of a moving object in a fluid. In particular, the peak values of the correlation function differ from the background by two times. It allows us to accurately detect the useful signal. Generalization of the proposed approach to the case of determination of the fluid flow rate does not require modification of the basic principles of installations or cross-correlation method. The scheme of the developed experimental setup is the following: X-ray source produces the radiation with a complex spectrum, which is directed to the pipe filled with a multicomponent mixture. One part of the X-rays passes through the windows made of material with the low absorption coefficient and the mixture. Another part of radiation passes through the pipe's walls and is not practically absorbed by the walls, thereby forming a narrow beam. The beam, having passed through a multicomponent mixture, becomes a carrier of information about its characteristics, as well as the dependence on the composition and parameters of multiphase liquids. The X-ray radiation propagates and is scattered due to the photoelectric effect and Compton scattering. A crystalline monochromator analyzer consists of two single-crystal plastic cores (111) and (100). A part of the X-ray beam satisfying the Bragg conditions diffracts on the crystal monochromator analyzer, the other part passes it without deviations. Differential crystalline monochromator-analyzer radiation is directed to the counter ionizing radiation. A two-channel scintillation counter ionizing radiation registers monochromatic radiation at low and high energy corresponding to the Bragg condition for the crystal monochromator-analyzer.

Keywords: Cross-correlation analysis, X-ray radiation, Fluid flow rate.

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1. INTRODUCTION

Investigation of dynamics peculiarities of the complex systems behavior is based on analysis of temporal changes of any parameter being a signal produced by this system. There are a lot of methods of the temporal series analysis, and one can emphasize such as following: 1) analysis of correlation dependence between the random quantities, measurement of the closeness and direction of the relationship among these quantities or attributes – correlation and regression analysis [1, 2]; 2) evaluation influence of one or several independent variables on one variable investigated (one-dimensional analysis) or on several independent variables (multidimensional analysis), search of fixed or variable covariates – factor analysis or analysis of covariance [3, 4]; 3) search of an effective method describing complex system based on their fractal nature (self-similarity) – fractal and multifractal analysis [5, 6]; 4) analysis of structure and dynamics of complex systems in the frame of the deterministic chaos theory and nonlinear dynamics [7, 8]; 6) representation of temporal signal as sets of periodic (basic) functions and spectral analysis of the local disturbances – classical Fourier and wavelet analysis [9, 10]. In this work, we present in detail application of cross-correlation analysis to determine velocity of a moving medium using dynamic signal being X-rays passed through this medium. Apparatus for computing correlation functions is widely used in the following areas: medicine, microelectronics, mechanics, logistics, economics, spectroscopy, chemical composition analysis, etc.

In particular, X-ray irradiation of the disordered inhomogeneous systems and application of cross-correlation allows us to determine the chemical composition of the substance and characteristics of object investigated [11, 12].

2. THEORETICAL BACKGROUND

Cross-correlation is a standard method of estimating the correlation degree of sequences.

Let us consider two rays $x(i)$ and $y(i)$ with time delay t, where $i = 0, 1, 2, \ldots, N$, then the correlation coefficient r is determined as:

$$r = \frac{\sum_i \left[\left(x(i) - mx\right)\left(y(i-\Delta t) - my\right)\right]}{\sqrt{\sum_i \left(x(i) - mx\right)^2}\sqrt{\sum_i \left(y(i-\Delta t) - ym\right)^2}}, \qquad (1)$$

where mx and my are the average values of the corresponding series. Time delay t and length of correlation series could be less than N, e.g., goal may be the verification of correlation for the limited set of measurements. Coefficient $r = 1$ lies in the range of $-1 \le r \le 1$ and the boundary values of this range point out to maximum correlation. When $r = 0$, correlation is absent. For the case of correlation coefficient equal to unity, there is a coincidence of the series and, accordingly, the maximum degree of correlation. When correlation coefficient is close to the unity in absolute value, but has a negative value, there is an inverse correlation, i.e., it is a contrary relationship between two variables such that they move in opposite directions.

In problem under consideration, we should determine the chemical composition and velocity of fluid flow in well using the X-ray technique. When X-rays pass through the fluid layer, one part of the energy is ab-

sorbed by substance and another part could be detected. Thus, using the difference between energies absorbed by various parts of detector and initial energy emitted by radiation source, one can determine the chemical composition of a fluid.

Calculating correlation coefficient (1) between experimental data at various time moments, we can determine velocity of the fluid flow.

Sets of data from one detector at fixed point in time is $x(i)$ series and using Eq. (1) and data $y(i-\Delta t)$ from another detector with various time delay Δt_0, one can determine Δt, at which there is maximum correlation coefficient r. When r has maximum value, we consider that the intensity profile absorbed by detectors possesses maximum correlation with time delay Δt_0. This fact allows us to assert that in plane containing lines of the X-ray directions from source to detecting sensor, there is fluid layer with similar chemical composition, which overcomes distance between the detecting sensors L during Δt_0. Therefore, in first assumption the velocity of the fluid flow can be found as

$$V = L / \Delta t_0. \quad (2)$$

To test this method, the test bench was constructed. The main goal of experimental investigation was the demonstration of the principle possibility of determining the flow rate of an inhomogeneous fluid in a pipe using X-rays.

3. EXPERIMENTAL SETUP

The schemes of experimental facility and test bench are presented in Figs. 1, 2.

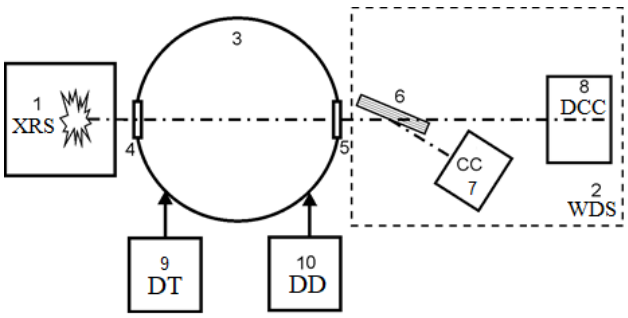

Fig. 1 – Installation for determination of component composition of a multicomponent fluid flow

X-ray source 1 produces radiation with complex spectrum, which is directed to pipe 3 filled with a multicomponent mixture. One part of X-rays passes through windows 4 and 5, which made of material with low absorption coefficient, and a mixture. Another part of radiation gets through pipe's walls 3 and is not practically absorbed by the walls, thereby forming a narrow beam. The beam, having passed through a multicomponent mixture, becomes a carrier of information about its characteristics, as well as dependence on the composition and parameters of multiphase liquids. The X-ray radiation propagates and is scattered due to the photoelectric effect and Compton scattering. Passed without interaction with windows 4 and 5 and the flow of a multiphase fluid the X-rays goes to a crystalline monochromator analyzer 6, consisting of two single-crystal plastic cores (111) and (100). A part of the X-ray beam satisfying the Bragg conditions diffracts on the crystal monochromator analyzer 6, the other part passes it without deviations. Differential crystalline monochromator-analyzer 6 radiation is directed to the counter ionizing radiation 7. A two-channel scintillation counter ionizing radiation 7 registers monochromatic radiation at low and high energy, corresponding to the Bragg condition for the crystal monochromator-analyzer 6.

The radiation transmitted without deviation enters the control sensor (stabilization monitor) X-ray intensity 8, which records the total current generated by the radiation in a sensitive volume, which carries information about the integrated radiation intensity at a specific point in time, and is used for the monitoring.

At the same time, sensors measuring pressure 9 and temperature 10 of a multiphase fluid measure the temperature and pressure of the fluid flow used to refine the values of the absorption coefficients of the flow components.

Data from sensors controlling and stabilizing the intensity of X-ray radiation 8, measuring pressure 9 and temperature 10 of a multi-phase liquid and from a two-channel scintillation counter ionizing radiation 7 is fed to a computer or controller.

4. MEASUREMENT AND RESULTS

The pipeline section, which was located vertically, was filled with a liquid with a density of $\rho = 920$ kg/m^3. A device that generates air bubbles was installed at the bottom of the pipeline.

An X-ray source and two sensors that detect radiation transmitted through a liquid are diametrically opposed with respect to the longitudinal axis of the pipe and beyond. The sensors consist of $N = 128$ lined-up elements of 400×200 μm in size with a frequency of $f = 2$ kHz, i.e. sensor readings are taken with a time delay $\Delta t = 500$ μs.

During the experiment, one air bubble is generated at a certain frequency. The registration of the bubble by the equipment used and the determination of the speed of movement by the method of cross-correlation will confirm the fundamental possibility of determining the flow velocity by the proposed method.

The result of the experiment are data sets from each sensor $I(N,m)$ at different points in time. The data set is an $N \times m$ matrix, where N is the number of sensor elements, m is the number of measurements separated by a time interval Δt.

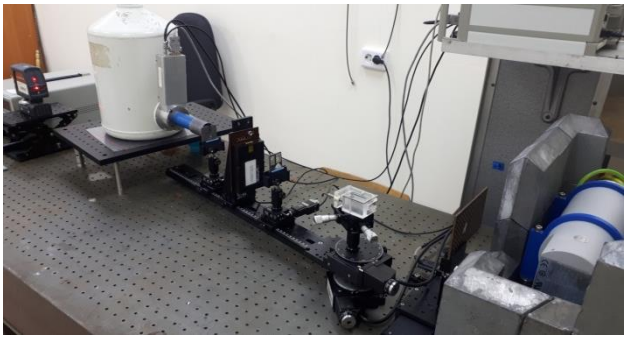

Fig. 2 – Photo of the laboratory stand

$$I_1(N,m)=\begin{pmatrix} I_1(N_1,m_1) & \cdots & I_1(N_{128},m_1) \\ \vdots & \ddots & \vdots \\ I_1(N_1,m_N) & \cdots & I_1(N_{128},m_N) \end{pmatrix}, \quad (3)$$

$$I_2(N,m)=\begin{pmatrix} I_2(N_1,m_1) & \cdots & I_2(N_{128},m_1) \\ \vdots & \ddots & \vdots \\ I_2(N_1,m_N) & \cdots & I_2(N_{128},m_N) \end{pmatrix}, \quad (4)$$

where $I_1(N,m)$ is the radiation intensity detected by the first sensor, $I_1(N,m)$ – by the second one.

The cross-correlation method is used to determine the velocity of a bubble. It is necessary to determine the correlation coefficients between the experimental data of the first sensor at a fixed point in time $I_1(N, m_0)$ and the data of the second sensor at different points in time $I_2(N, m_i)$. If a maximum correlation appears between the dependences, the time $\Delta t_0 = \Delta t(m_0 - m_i)$ will be determined, for which the bubble will cover the distance L from the first sensor to the second.

Fig. 3 shows the dependences of the radiation intensity recorded by the elements of the first sensor $I_1(N,m)$ at different points in time. From Fig. 3 it can be seen that the sensor readings are in the vicinity of the average value $I_0 = 5 \cdot 10^4$ a.u. The discontinuous behavior of the $I_1(N,m)$ dependence is due to the presence of internal and external noise signals. It also follows from Fig. 3 that at different points in time, there is a change in the value of $I_1(N,m)$, which is associated with the presence of an air bubble on the line connecting the X-ray source and detector. To distinguish a signal indicating the presence of an object in a liquid, it is necessary that the signal arriving at the detector should exceed the noise signal in amplitude. For such purposes, the quantitative signal-to-noise characteristic SNR = $I/\langle A^2 \rangle$ is used, where $\langle A^2 \rangle$ is the average value of the intensity of the noise signal. The signal is considered satisfactory when the value of SNR > a, where $a = const$, is greater than one.

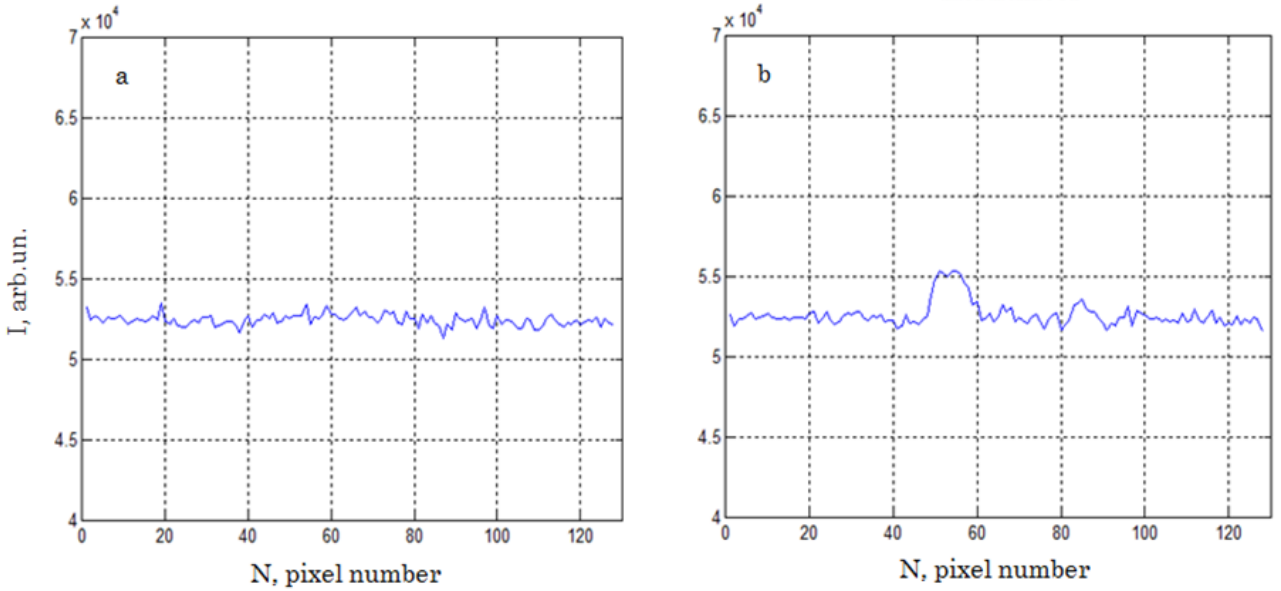

Fig. 3 – The dependence of the radiation intensity of the sensor elements $I_1(N,m)$ at different moments of times (a) – m_0, (b) – m_2

From Fig. 3a, it follows that the value $I_1(N, m)$ is within the limits of noise, that indicates the absence of any inhomogeneities between the radiation source and the detector. As the observation time increases, a maximum appears on the $I_1(N, m)$ dependence, which corresponds to a signal with an SNR >1, that indicates the appearance of a bubble. With a further increase in the observation time, the signal increases in amplitude that indicates that the bubble passes the detector (Fig. 3b).

Further, the bubble should be registered by the second sensor, at the output of which the dependences $I_2(N, m)$ should be observed, which characterize the appearance of heterogeneity in the liquid. After comparing the data from detectors, it can be concluded that the dependences have identical behavior when registering air bubbles. Thus, to determine the velocity of an air bubble in a liquid, it is necessary to determine the value $\Delta t_0 = \Delta t$ $(m_{10} - m_{20})$, where m_{10} is the moment of detection of the bubble by the first detector, m_{20} is the measurement at which the same bubble was recorded by the second sensor.

To determine the points in time at which the same heterogeneity (bubble) was registered by the first and second detectors, the cross-correlation method is used. To calculate the correlation coefficient r by the formula (1), we select from (3) a set of experimental data $I_2(N, m_k)$ for measuring m_k, at which an air bubble is observed before the second detector. Further, the value of $I_2(N, m_k)$ is set in accordance with the measurements made by the first sensor $I_1(N, m_i)$, which occurred on the time scale earlier than for the second detector, i.e. $i \le k$.

According to the formula (1), we determine the correlation coefficient r between measurements $I_2(N, m_k)$ and $I_1(N, m_i)$. The result is shown in Fig. 4.

From Fig. 4 it can be seen that the correlation coefficient changes periodically. The presence of peaks in the dependence $r(m_i)$ indicates that the dependence $I_2(N, m_k)$ correlates with the series of measurements $I_1(N, m_i)$, in which air bubbles are recorded. The experiment was set

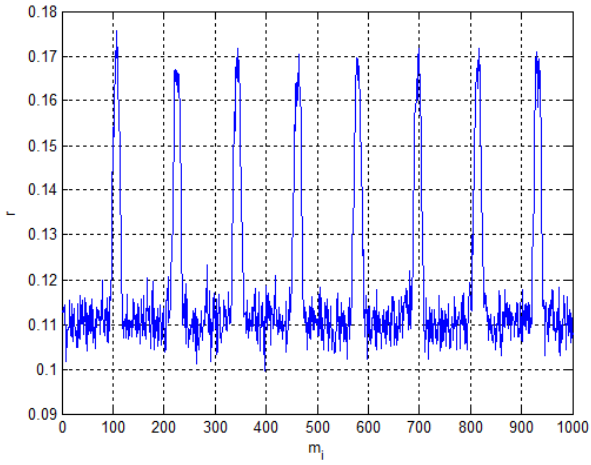

Fig. 4 – Dependence of the correlation coefficient $r(t_i)$ between measurements $I_2(N, m_k)$ and $I_1(N, m_i)$, corresponding numbering $i \le k$

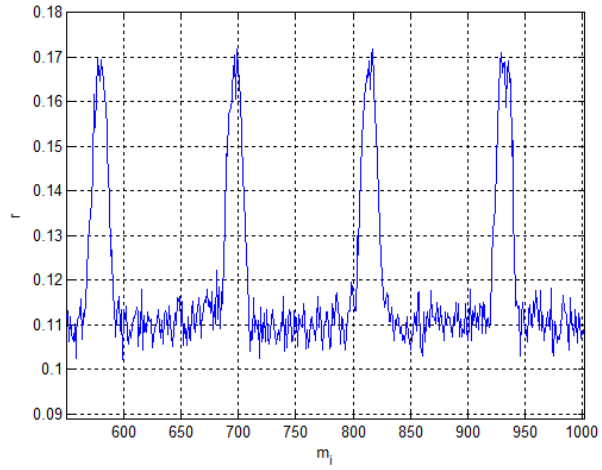

Fig. 5 – Dependence of the correlation coefficient $r(m_i)$ in the neighborhood of m'_{10}

up in such a way that the formation of bubbles is repeated with a certain period in the same neighborhood of the space and with close linear dimensions. This explains the periodicity of the peaks of the dependence $r(m_i)$ and approximately the same values of r for measurements in which bubbles are fixed.

To select the measurement m_{10}, in which the first detector detects a bubble corresponding to the measurement $m_k = m_{20}$ of the second detector, we use the dependencies $I_1(N, m_i)$ presented in Fig. 3. Using the measurement data, we can determine the velocity of the bubble, if we calculate the time interval Δt_0 during which the bubble was recorded by the first detector. The bubble size l_0 can be estimated from the number of detector elements for which the SNR value over the time interval Δt_0 exceeded one.

During the course of calculations, it was determined that the linear size of the bubble is $l_0 \approx 6$ mm, and the time interval is $\Delta t_0 \approx 0.046$ s, which corresponds to the speed of movement of the bubble $V_0 \approx 0.13$ m/s. The distance between the sensors is $L = 0.05$ m, therefore, the approximate value of the time interval during which the bubble covered the distance L is calculated as $\Delta t' = L/V_0 \approx 0.375$ s.

The value of V_0 can be taken as a zero approximation, since the time calculations $\Delta t'$ and the size l_0 are estimated and depend on such parameters as SNR, the size of the detector element, f, etc. In this connection it is necessary to determine the speed by a more accurate method.

After calculating $\Delta t'$, it is possible to determine in which neighborhood of the measurements m_i for the first sensor the bubble of interest was registered.

Taking into account that the time interval $\Delta t = 500$ μs passes between measurements, we define the measurement of the first sensor at which the signal was recorded $m'_{10} = \Delta t' / \Delta t \approx 780$. The dependence of $r(m_i)$ in the neighborhood of m'_{10} is shown in Fig. 5.

From Fig. 5 it can be seen that the measurement in which a peak $r(m_i)$ is observed and close to m'_{10} corresponds to the number $m_i = 815$. The value $m_i = 815$ corresponds to the time range $\Delta t_0 = \Delta t \cdot m_i \approx 0.4075$ s, which corresponds to the time of bubble movement between the first and second sensors.

Thus, in the first approximation, the velocity of a bubble in a fluid V can be expressed by formula (2), therefore, the velocity of a bubble is equal to the value $V = L/\Delta t_0 = 0.123$ m/s.

Thus, the paper shows the fundamental performance of the proposed method for determining the velocity of objects moving in a fluid. The generalization of this model to the case of determining the flow rate of a liquid does not require a change in the principles of operation of the installation or the method of cross-correlation. When X-rays are scanned by a flow of inhomogeneous fluid flowing in the pipeline, the readings of the sensors registering the transmitted radiation will be similar to the dependencies shown in Fig. 3 and Fig. 4, but with a more complex pattern due to the presence of a larger number of inhomogeneities. The determination of the flow velocity will also be determined using the cross-correlation method, i.e. determining the time of passage of the same layer of fluid between the sensors.

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Застосування методу крос-кореляційного аналізу для вимірювання швидкості потоку рідини на основі рентгенівського випромінювання

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У роботі продемонстровано принципову схему застосування методу крос-кореляційного аналізу для визначення швидкості руху рухомого об'єкта в рідині. Зокрема, пікові значення кореляційної функції відрізняються від фонових в два рази. Це дозволяє точно визначити корисний сигнал. Узагальнення запропонованого підходу до випадку визначення витрати рідини не вимагає модифікації основних принципів інсталяції або методу крос-кореляції. Схема розробленої експериментальної установки полягає в наступному: джерело рентгенівського випромінювання зі складним спектром спрямовується на трубу, заповнену багатокомпонентною сумішшю. Одна частина рентгенівського випромінювання проходить через вікна, виготовлені з матеріалу з низьким коефіцієнтом поглинання і сумішшю. Інша частина випромінювання проходить через стінки труби і практично не поглинається стінами, утворюючи тим самим вузький пучок. Промінь, пройшовши через багатокомпонентну суміш, стає носієм інформації про його характеристики, а також залежності від складу і параметрів багатофазних рідин. Рентгенівське випромінювання поширюється і розсіюється за рахунок фотоефекту і комптонівського розсіювання. Аналізатор кристалічного монохроматора складається з двох монокристалічних пластикових стрижнів (111) і (100). Частина рентгенівського пучка, що задовольняє бреггівським умовам, дифрагує на аналізаторі кристалічного монохроматора, інша його частина проходить без відхилень. Диференціальне випромінювання кристалічного монохроматора-аналізатора спрямоване на протидію іонізуючого випромінювання. Двоканальний сцинтиляційний лічильник іонізуючого випромінювання реєструє монохроматичне випромінювання при низькій і високої енергіях, що відповідає умові Брегга для кристалічного монохроматора-аналізатора.

Ключові слова: Крос-кореляційний аналіз, Рентгенівське випромінювання, Швидкість потоку рідини.